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As defense budgets continue to shrink, cost-effective methods for the accurate and timely acquisition of aerodynamic data must be developed. Traditionally, wind tunnels have fulfilled this role at both the conceptual and developmental stages, as well as throughout the service life of an aircraft. However, although wind tunnels are a trusted and valuable data source that provide consistent repeatable data upon which to construct aerodynamic models, they also have inherent limitations such as blockage effects, wll and sting interference, and flow variations. Because of these constraints and due to the elevated angles-of-attack and sideslip that modern fighter aircraft are capable of, wind tunnels can be limited in their ability to cover an entire flight envelope.

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SIMULATION SUPPORT OF A 17.5% SCALE F/A-18E/F REMOTELY PILOTED VEHICLE

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Abstract

A simulation of a 17.5% scale F/A-18E/F remotely piloted vehicle (RPV) has been created and used for both engineering analysis and pilot training. The RPV team, comprised of personnel from Naval Air Warfare Center Aircraft Division, Patuxent River, North Carolina State University, and Bihrle Applied Research, Inc., has used the simulation as a tool for vehicle performance analyses, flying qualities assessments, and pilot training to reduce project risk. This paper details how the simulation was created and provides information pertaining to specific simulation models. The paper discusses the unique application of the simulation in real time using the Navy's Manned Flight Simulator facility. Lastly, the paper highlights results from a takeoff performance analysis which ultimately defined the takeoff configuration for the first flight of the RPV.

Introduction

In these times of shrinking budgets and the growing dependence upon simulation for flight research, aircraft development, and flight test support, the timely acquisition of aerodynamic data for use in high-fidelity simulation models has become increasingly important. Traditionally, data collected from wind-tunnel tests of sub-scale models have been the primary source of such simulation models, but these databases are assembled from a variety of test techniques, such as high- and low-speed static tests, rotary balance tests, and forced oscillation tests. Although necessary, the creation of an aerodynamics database with these data has several inherent draw backs. Dissimilarities among the data collection methods and inconsistencies in the tunnels themselves make creation of accurate simulation aerodynamics models challenging[1,2]. In addition, test data from wind-tunnels can be corrupted by wall and sting interference, flow variations, and blockage effects. A final drawback is that the scope of wind-tunnel testing can be limited because of the facility and test apparatus. This becomes a problem when attempting to model large variations in flow angle. For example, during F/A-18C/D departures, sideslip can exceed 45°[3] but the comprehensive collection of wind tunnel data at sideslips of this magnitude is difficult.

Technical issues are only part of the dilemma in using wind tunnel data for simulation model development; logistics can cause additional problems. With recent facility closures such as the 30- by 60-Foot Tunnel at the NASA Langley Research Center, wind tunnel entries may not be easy to obtain. Furthermore, the facilities that are available may not be as well-suited to the test requirements due to, for example, incompatibility of the test section with the model size. For these reasons, alternative, cost-effective methods for acquiring accurate aerodynamics data for the creation and improvement of simulation models must be explored.

One innovative solution for augmenting wind-tunnel data is through the use of data extracted from sub-scale, unpowered, free-flight models commonly known as drop models[4,5,6]. Although useful, these inertially-scaled free-flight models have historically been unable to generate large amounts of data in a timely fashion due to technical, logistic, and economic limitations. Recent advances in sub-scale propulsion, small-scale instrumentation systems[7] and software tools to aid parameter identification[8], have contributed to the feasibility of extracting aerodynamic data from such aircraft models in a timely manner.

A foreseeable advantage in using a powered sub-scale model to collect data for simulation validation is that, in addition to the greater flight duration when compared to a drop model, the rapid recovery and turn-around of a powered remotely piloted vehicle (RPV) will permit two to three approximately 15-minute data collection flights per flight day. By contrast, drop model programs have averaged one flight every 12 to 14 days, with a demonstrated capability to fly as frequently as once every three days. In addition, the average flight

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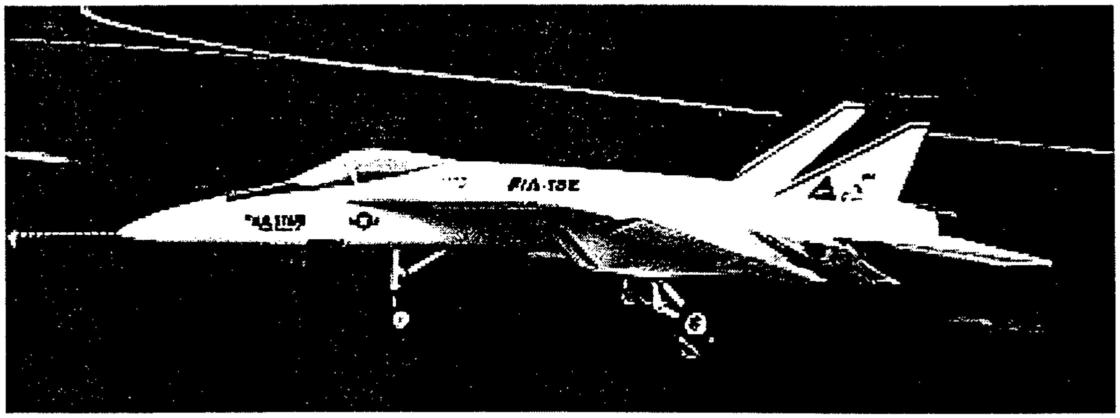


Fig. 1 Photograph of 17.5% scale F/A-18E/F RPV.

duration of a drop model is approximately 2 minutes[9]. In any given flight, a powered sub-scale model could potentially collect more than ten times the data than an unpowered drop model.

In addition to its ability to collect simulation validation data, a powered RPV may be well suited to compliment flight research using drop models. A powered RPV would enable test teams to investigate phenomena occurring in flight regimes that are typically difficult to reach with a drop model. For example, a powered RPV will be able to achieve prolonged straight and level flight as well as sustained accelerated turns, regimes where drop models are limited in capability.

The Naval Air Warfare Center Aircraft Division (NAWCAD), North Carolina State University (NCSU), Bihrle Applied Research, Inc. (BAR), and SWB Turbines, Inc. (SWB) have teamed to construct a 17.5% scale remotely piloted vehicle model of the F/A-18E/F (Fig. 1). The goal of the first phase of the project is to prove that a powered sub-scale model, equipped with the proper instrumentation system, can collect data useful for simulation aerodynamics model development and validation. Subsequent phases will focus on supporting simulation validation, F/A-18E/F flight test, and generalized flight research. An additional project goal is the acquisition of multiple wind tunnel entries with the RPV aeroshell to obtain a set of validation data. Using this controlled data set collected with the same aerodynamic model, flight data from the RPV may be directly correlated to an independent data source. This will permit a direct assessment of the feasibility of the RPV concept, and enable the quantification of unknown tunnel effects and/or induced engine and thrust effects. Unfortunately, as of this writing, the primary obstacle to this goal is the availability of a wind tunnel with a test section large enough to accommodate the RPV aeroshell.

Because of the relatively high risk associated with this research, the use of high-fidelity simulation was mandated. A six degree-of-freedom simulation of the RPV was derived from the full-scale F/A-18E/F simulation, interfaced with the Navy's Manned Flight Simulator (MFS) facility[10], and used for engineering analysis and pre-flight training purposes.

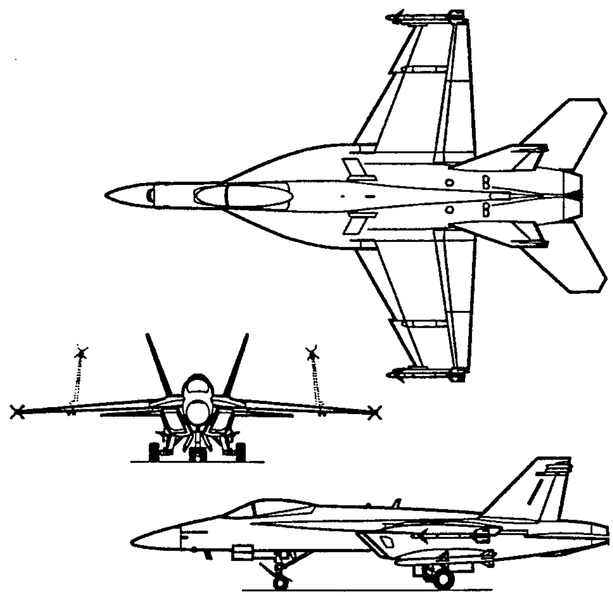


Fig. 2 Three-view diagram of F/A-18E/F.

F/A-18E/F 17.5% Scale Model

The F/A-18E/F RPV is a 130 lb, 17.5% geometrically-scaled model of the McDonnell Douglas F/A-18E/F Super Hornet (Fig. 2). The RPV was constructed using advanced composites by Foley Manufacturing, Inc., and is powered by two SWB-3 kerosene-burning turbojets that are each rated at 35 lbs static sea level thrust. State-of-the-art amateur radio control equipment is used to transmit pilot commands to ailerons, leading-edge (LEF) and trailing-edge flaps (TEF), rudders, stabilators, and engines; the leading-edge extension (LEX) vents and spoilers are currently inoperative and fixed in their undeflected positions. The RPV has fully retractable landing gear, complete with brakes and nose wheel steering. For the first series of test flights, an airspeed probe and engine RPM sensor will be used to measure a limited amount of

information which will be recorded on board. Shortly after first flight, rate transducers, accelerometers, vertical gyros, angle-of-attack probes, pressure sensors, and telemetry will be added to the instrumentation system.

In later phases of the program, the RPV will be equipped with a video camera and various other systems to support ground-based cockpit operations.

RPV Simulation

The RPV simulation model was adapted from the full-scale, six degree-of-freedom F/A-18E/F simulation model developed under contract by McDonnell Douglas Aerospace and provided to the Navy. Both simulation models are capable of running in real-time, and use the Controls Analysis and Simulation Test Loop Environment (CASTLE) generic simulation architecture[11]. The simulation currently represents the RPV first-flight configuration, scheduled to be flown in late Spring of 1996.

Of the five main models used in the RPV simulation, the engine, weight and balance, and the controls system models were created by the Flight Vehicle Simulation Branch at NAWCAD using information provided by NCSU, BAR, and SWB. The landing gear and aerodynamics models used by the RPV simulation are slightly modified versions of the full-scale simulation models.

Aerodynamics Model

The RPV aerodynamics model was derived from the full-scale F/A-18E/F real-time simulation at NAWCAD. The only modifications made were to geometric constants such as mean aerodynamic chord, wing span, and reference area, and an adjustment to one of the independent variables in the ground effect function table which scaled this effect to the geometry of the RPV.

The F/A-18E/F aerodynamics model consists of a rigorous assortment of non-linear basic and incremental function table data in coefficient form. These data were collected from low- and high-speed static wind tunnel tests, with dynamic data provided by both forced oscillation and rotary balance tests. These data are linearly interpolated, and combined via a coefficient summary to produce the total force and moment coefficients acting on the airframe during each simulation time frame. Dynamic data are first combined using the Kalviste technique[12], then summed with the static data. Aerodynamic increments for a variety of store loadings, although not generally applicable to the RPV, are available.

Engine Model

The RPV engine model is also based on non-linear function tables constructed from static thrust and engine speed curves supplied by the RPV engine manufacturer, SWB. Dynamics are modeled via first-order lags. Radio transmission delays of the pilot inputs are also incorporated into the model. Malfunctions include single and dual engine failures.

Weight and Balance Model

The RPV weight and balance model is comprised of actual measurements of the RPV weight and center of gravity (c.g.), and estimates of the inertial characteristics. Initial approximations of pitch inertia have recently been validated to within 5% of measured data. Assuming that roll and yaw inertia estimates were of the same accuracy, a sensitivity analysis was conducted with the RPV simulation by varying the inertial characteristics in all three axes. This study revealed little discernible effect on predicted flying qualities, providing increased confidence in the use of the roll and yaw estimates for handling qualities work. These intertias will be measured prior to first flight. Provisions were made for full- and empty-weight conditions, with linear interpolation of the data between the two states to determine the weight and c.g. characteristics of partial-fuel conditions.

One typically minor aspect of full-scale weight and balance modeling that became important for the RPV simulation was the c.g. shift with main landing gear deflection. The main landing gear of the RPV is similar in geometry to the full-scale F/A-18E/F in that the main wheels pivot rearward as the landing gear strut is compressed. On the full-scale aircraft, the resulting c.g. shift is negligible, but in the case of the RPV, this equated to a c.g. shift of approximately 1.3% mean aerodynamic chord (MAC).

Control System Model

Figure 3 shows a block diagram representation of the RPV's first-flight control system as modeled in the simulation. For first flight, a simple control system was created that provided pitch control through collective stabilator deflection, roll control through differential aileron deflection, and yaw control through collective rudder deflection; all three axes are trimmable. Once again, radio transmission delays of pilot inputs are included. For the RPV, flaps were initially intended for take-off and landing use only (i.e., no scheduling of maneuvering flaps), so provisions were made in the simulation for half, full, and UP/AUTO (0° LEF/0° TEF) flap positions. As previously noted, the LEX vents and spoilers will not be functional on the RPV for the first series of flights, so these surface positions were "hard-wired" closed in the simulation. Simple failures of the primary control surfaces were modeled.

The RPV actuators are modeled in the simulation as second-order, rate-limited lags, and were based on time-response information of the JR4031, JR4421, and JR4721 electric servo motors selected for use in driving most of the RPV control surfaces. A model of the Condor PS-050 high power electric servo motor, used

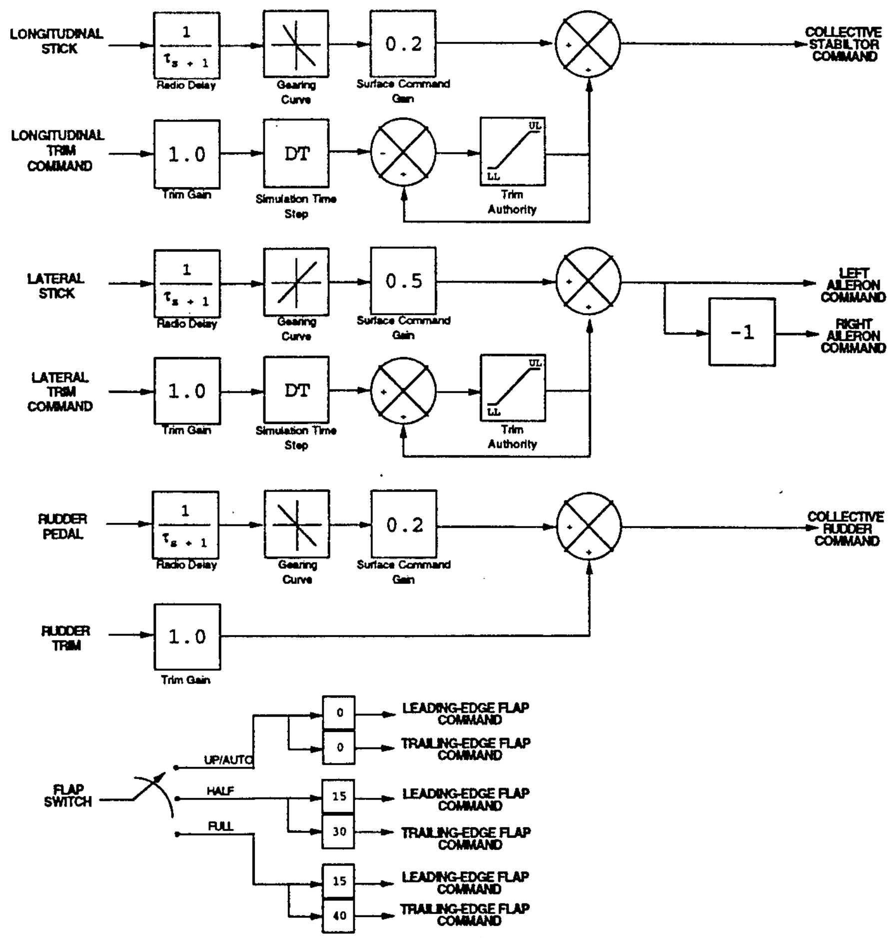


Fig. 3 Block diagram of RPV simulation control system model.

to drive the RPV flaps and stabilators, is currently under development by NCSU.

Landing Gear Model

The landing gear model used for the RPV simulation is a scaled-down version of the physically representative landing gear model used in the full-scale F/A-18E/F simulation at NAWCAD[13]. Each landing gear component, nose and main, is modeled as a single, decoupled strut-wheel assembly. RPV-specific strut reaction force and deflection data provided by NCSU were incorporated into the model. The results were then verified by NAWCAD using NCSU measurements.

Real-Time Interface

A unique aspect of the RPV simulation is the ability to interface it in real-time with an adapted radio controller (R/C) or one of the MFS facility's F/A-18 cockpits. The radio controller is similar to the one that will be used by the pilot during the initial phase of the RPV flight program. In this configuration, a fixed eyepoint location near one of the runways contained in the image generation (IG) database is presented, and the RPV simulation drives a moving model contained within the IG, indicating to the pilot the relative position of the RPV to that eyepoint. In the cockpit mode, the RPV simulation drives the image generation system in exactly the same way other MFS simulations do. This real-time interface will be used to support later phases of the program in which the RPV will be controlled by a pilot in a remote, ground-based cockpit.

Early in the RPV simulator development effort, the MFS 40-foot dome, with its target projectors and IG system, was used to provide visual cues to the pilot during real-time operations. The target projectors were slaved to the IG moving model, and were used in an effort to highlight the position of the RPV when it became too distant for the pilot to discern it from the rest of the IG visual scene. However, the ability of the target projectors to enhance the poor visual scene resolution was minimal, and their low reliability finally forced the abandonment of this set-up in favor of the facility's new helmet-mounted display (HMD) system. Using the HMD provides a more realistic environment, much greater visual scene resolution, and better system reliability, while only sacrificing some freedom of

movement and the ability to quickly and easily glance down at the radio controller.

RPV Program Support

In addition to providing pilot training, the F/A-18E/F RPV simulation has been used to support the RPV first flight readiness program in several ways, primarily through the investigation of control power issues, the assessment of flying qualities, and the exploration of takeoff performance issues.

Engineering Analysis

Flying Qualities

Early use of the RPV simulation for engineering analysis quickly revealed potential flying qualities issues. The primary problem was static stability, both longitudinally and directionally. As would be expected when using the relaxed stability margins intended for the full-scale F/A-18E/F, the RPV became longitudinally unstable at very low angles-of-attack. Then, as the longitudinal instability caused angle-of-attack to rapidly increase, and with the flaps fixed in the 0°/0° UP/AUTO position, directional stability degraded to the point where the RPV would enter a violent, nose-slice departure. A secondary contributor to this was the over-abundance, primarily longitudinally, of control power, combined with small vehicle inertias. The stabilators provided enough pitch power to abruptly over-command RPV pitch response, which would result in undesired angle-of-attack excursions and airframe overstress. The solution to this problem was to reduce the control surface authority provided to the pilot while ensuring adequate static stability. In the case of the RPV, a c.g. position of 21% MAC provided acceptable longitudinal stability, and thus, departure resistance. After extensive simulation studies, gains of 0.2, 0.5, and 0.2 were placed on the longitudinal, lateral, and directional axes command paths respectively; these gains reduced the full-authority control surface commands modeled in the RPV simulation via the control system gearing curves. Since the original plan for the RPV did not call for scheduling of the leading- and trailing-edge flaps for first flight, initial flights will be restricted to half or full flaps. However, simulation studies indicate that by scheduling the RPV flaps with angle-of-attack, a marked increase in directional stability could be realized even at longitudinal static margins approaching zero. Such a flap schedule will be incorporated in the future.

Other analysis areas in which the simulation proved useful were in the extraction of linear aerodynamics models for control power assessments and Eigenvalue analysis of the dynamic stability modes of the RPV, the calculation of anticipated hinge moments to assist in accurate selection of the RPV actuators, and the determination of sensor bandwidth and resolution requirements.

Takeoff Performance Analysis

A study was conducted to determine the necessary amounts of thrust and pitch authority required to successfully operate the RPV from the NCSU flight facility. Initially, control surface combinations of 15° LEF, 20° TEF, no rudder toe-in, and ±5° of stabilator authority had been selected as the baseline takeoff configuration (15°/20°/0°). Table I contains the test matrix used in the investigation.

Table I. Real-time RPV minimum takeoff distance test matrix.

Configuration	Maximum Available Thrust (TMAX ≈ 68 lbs)	Maximum Stabilator Available
1	45% TMAX	±5.0°
2		±7.35°
3		±9.7°
4	55% TMAX	±5.0°
5		±7.35°
6		±9.7°
7	65% TMAX	±5.0°
8		±7.35°
9		±9.7°
10	75% TMAX	±5.0°
11		±7.35°
12		±9.7°
13	85% TMAX	±5.0°
14		±7.35°
15		±9.7°
16	95% TMAX	±5.0°
17		±7.35°
18		±9.7°
19	105% TMAX	±5.0°
20		±7.35°
21		±9.7°

Seven engine force levels, varying from 45% to 105% of the approximately 68 lbs total maximum rated static thrust (TMAX) were used, as well as three maximum stabilator deflections (±5.0°, ±7.35°, and ±9.7°), all of which employed an exponential gearing curve similar to the one available in the RPV radio controller. The real-time test procedure began with the RPV stationary on the runway with maximum power lever angle. Approximately 5 seconds into the ground roll, full aft stick was applied and held until rotation; the total elapsed time of the takeoff roll was noted. Once in the air, the pilot climbed steadily for several seconds, simulating the clearance of a 50-foot obstacle, then executed a 90° heading change. During the tests, the RPV pilot was required to make comments concerning the handling qualities for the 65%, 75%, 85%, and 95% TMAX cases, at all maximum stabilator

deflections, based on his ability to control the RPV after takeoff, during climb out, and throughout the 90° heading change. Figure 4 contains a plot of minimum takeoff ground roll distances versus takeoff velocity for varying thrust levels and maximum stabilator deflections. It should be noted that the 45% TMAX line represents the minimum flyable thrust level. When this was combined with the ±9.7° maximum stabilator deflection, the RPV, although capable of rotating and climbing into the air, did not have enough thrust to power out of the resulting deep stall and maintain flight. In addition, it did not initially acquire enough altitude that could be "traded back" for airspeed before impact. Also of note regarding Fig. 4 is that, by using the engine manufacturer's thrust degradation curve as a function of ambient temperature, an equivalent %TMAX thrust level may be computed for any non-standard day. The resulting takeoff distance may be approximated through linear interpolation of the curves.

A second takeoff performance study consisted of performing pilot technique variations of the 65%, 75%, 85%, and 95% TMAX cases. For each of the 15°/20°/0° configurations, a gradual aft-stick pilot input (i.e., enough aft stick to rotate) was applied either 2 or 4 seconds after the recorded minimum takeoff times. This was done to study the handling qualities and takeoff distances with increased takeoff velocity using a more

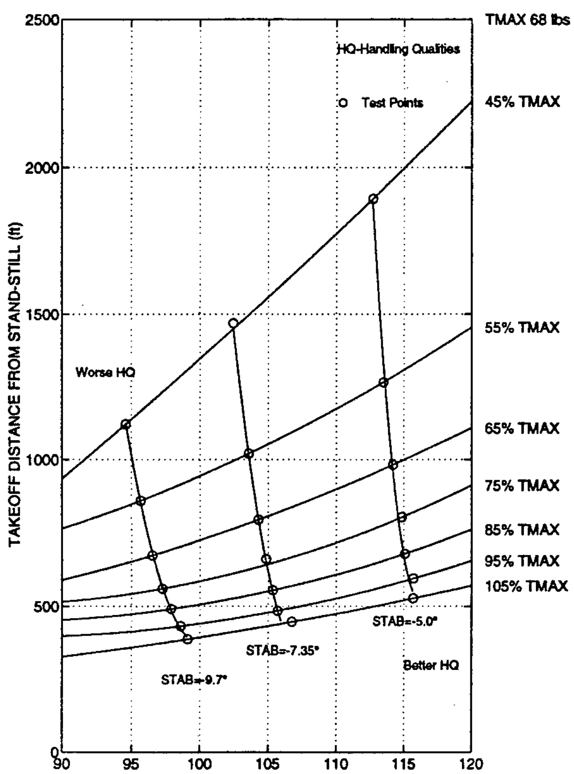


Fig. 4 Standard-day minimum takeoff distances for varying thrust levels and maximum stabilator deflections, (15°/20°/0°).

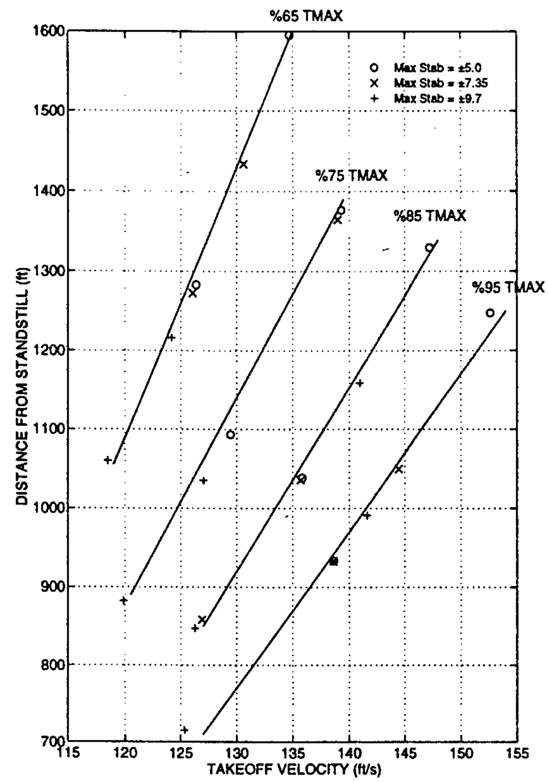
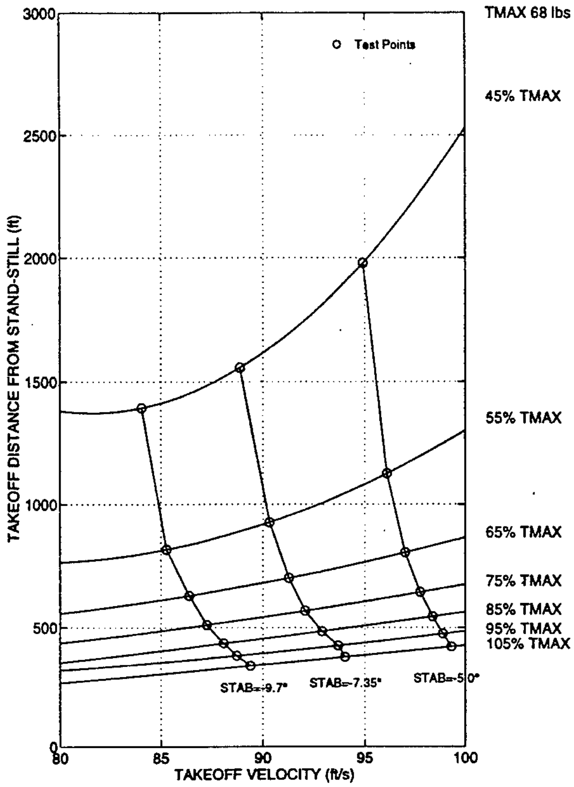


Fig. 5 Takeoff distances using delayed pilot input with varying thrust level and maximum available stabilator deflections, (15°/20°/0°).

realistic pilot technique. These results are presented in Fig. 5. While handling qualities did improve as expected, there was a generally marked increase in the required takeoff distance.

A final takeoff performance study was conducted to explore aerodynamic methods for reducing the takeoff distance, which was becoming an increasing concern given the takeoff distances predicted for the baseline configuration during the previous two studies, and the 700-foot runway length of the intended base of operation. These included the use of varying amounts of rudder toe-in (10°, 20°, 30°, and 40°), or a 30° TEF deflection. Reductions in takeoff distance with each of these configuration changes were noted, as well as any pertinent handling qualities attributes. Based on these results, it was concluded that a configuration employing 15° LEF, 30° TEF, and 20° rudder toe-in (15°/30°/20°) would provide the best combination of takeoff performance and handling qualities. This configuration was further explored. Figure 6 contains a plot of minimum takeoff ground roll distances for this proposed configuration versus takeoff velocity for varying thrust levels and maximum stabilator deflections, which, like Fig. 4, may be interpolated for non-standard day conditions. In almost every case, the 15°/30°/20° configuration reduced takeoff distance while providing acceptable flying qualities, the single exception being the 45% TMAX case, in which the configuration



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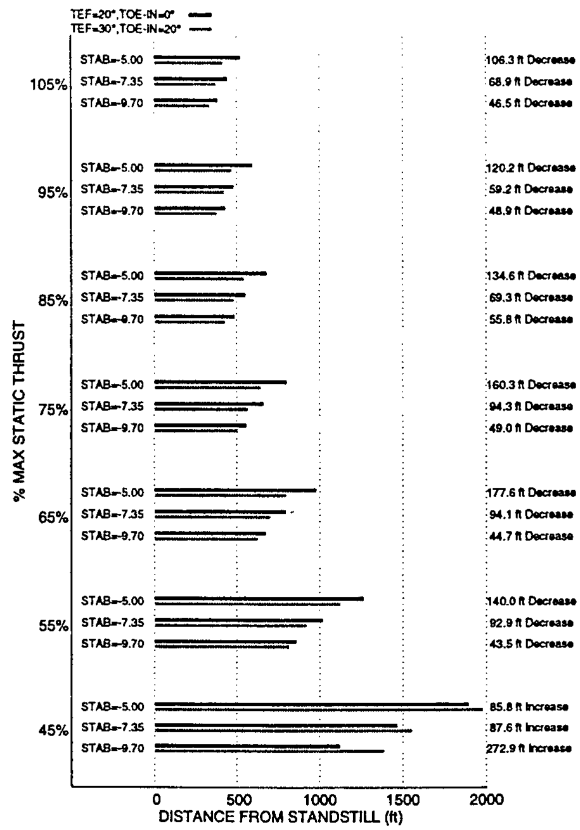

Fig. 7 Takeoff distance comparison between baseline and proposed configurations.

neither reduced takeoff distance nor was able to maintain flight. Figure 7 presents a direct comparison of minimum takeoff distance between the baseline configuration (15°/20°/0°) and the proposed configuration (15°/30°/20°).

Pilot Training

The F/A-18E/F RPV first flight test plan requires project pilots to fly the RPV simulation in real-time using the HMD interface at NAWCAD. During this training, the pilots were afforded the opportunity to familiarize themselves with predicted handling qualities of the first flight configuration, as well as develop and practice emergency procedures for a variety of failures.

Discussion of Results

The results of the takeoff investigation indicate that to achieve acceptable takeoff performance, the RPV's net engine force must be at least 75% TMAX. As Fig. 4 and 6 indicate, increased stabilator authority decreased the minimum ground roll, but for the 15°/20°/0° configuration, it also tended to degrade handling qualities. This is primarily the result of an over-abundance of pitch power for the given flap setting, which enabled the pilot to rotate the nose and take off before gaining sufficient airspeed for suitable flying qualities. However, this degradation in handling qualities was not apparent with the 15°/30°/20° configuration, making it desirable for reducing takeoff distance. Thus, it is recommended that the net engine force be at least 75% TMAX (although, net thrust forces in the 85% to 95% TMAX range are desired), takeoff flaps be set at 15° LEF and 30° TEF, rudders toed-in to 20°, and a maximum stabilator deflection of ±7.35° be employed (although as previously noted, ±9.7° would also be acceptable for this configuration).

Allowing the takeoff speeds to increase by delaying pilot input improved handling qualities at rotation and climb-out, but also increased ground roll significantly. Although a more realistic pilot input, this technique is not recommended for use with the 15°/20°/0° configuration due to runway length limitations at the intended base of operation. Use of this technique with the 15°/30°/20° configuration is more plausible, given its superior takeoff performance and generally acceptable handling qualities exhibited by all stabilator authorities.

Reaction of the project pilots to the simulator training was very positive. They found the resolution provided by the HMD adequate to the task of flying the RPV simulation despite the seeming bulk of the helmets and the lack of mobility that the system afforded. One problem that the pilots quickly noted was the poor contrast of the RPV visual model, which made it difficult for them to accurately discern its roll attitude. This was simply due to the default low-visibility color

scheme of the visual system model, which can be corrected through the use of a color scheme that contrasts the ventral and dorsal sides of the visual model. With regards to the simulation model itself, although initially skeptical of the reduced control surface authorities that were proposed for the RPV, the pilots were pleased with the handling qualities and control harmonies exhibited by these gains. Control feel was good in all axes, turn coordination was excellent, and no departure tendencies were exhibited. As a direct result of this training, the pilots became comfortable that the simulation control gains were appropriate to use as the nominal RPV surface authorities for first flight. In failure scenarios, the pilots were given an invaluable opportunity to assess the affects of various control surface and propulsion system failures. Although it was impossible for them to directly discern the nature of each individual failure, this exercise gave them insight into how the RPV might globally react to failures and what difficulties they might experience in first determining that a failure existed, then in returning the RPV safely to the ground. In all cases, the pilots were able to quickly identify that some failure had occurred, and convince themselves that the RPV maintained sufficient controllability for a safe landing.

Summary and Conclusions

A simulation was created to model a powered 17.5% scale model of the F/A-18E/F. Engineering analyses using the simulation enabled the RPV team to rapidly evaluate the stability and controllability of the RPV while in flight, select hardware and sensors suitable to the anticipated flight envelope of the RPV, and enhance overall project safety through risk reduction. The RPV exhibits acceptable flying qualities in all configurations, and preliminary studies indicate handling qualities may be further improved, principally for high angle-of-attack flight, through the use of maneuvering (i.e., scheduled) flaps. Takeoff performance studies indicated that the RPV needs at least 75% TMAX, a trailing-edge flap deflection of 30°, and rudder toe-in of 20° to achieve adequate takeoff performance at the intended base of operation. The MFS real-time simulation promises to be a valuable asset for pilot training. The pilots have been able to develop and practice emergency procedures, as well as become familiar with the predicted handling qualities of the RPV.

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